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MODELLING OF HIGH TEMPERATURE HEAT TREATMENT OF WOOD USING THERMOWOOD TECHNOLOGY

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ABSTRACT

Heat treatment of wood at relatively high temperatures (in the range of 180–240°C) is an effective method to improve the dimensional stability and to increase the biological durability of wood. During the heat treatment process, the heat and mass transfer takes place between the solid and the drying medium, and the moisture evaporation occurs within the solid due to the capillarity action and diffusion. In this article, a coupling method is presented for high temperature heat treatment of wood based on ThermoWood technology. A three-dimensional mathematical model considering the simultaneous unsteady heat and moisture transfer between a gas phase and a solid phase during heat treatment has been developed. The conservation equations for the wood part are obtained using the diffusion equation with variable diffusion coefficients, and the 3-dimensional incompressible Reynolds-averaged Navier-Stokes equations have been solved for the flow field. The coupling between the two parts is achieved by expressing the continuity of the state variables and their respective fluxes through the interface. A detailed discussion of the computational model and the solution algorithm is given.

INTRODUCTION

Wood, a composite of cellulose, hemicelluloses, lignin, and extractives, is commonly used as engineering and structural material. Unprotected wood exposed to outdoor conditions undergoes a variety of degradation reactions induced by diverse factors such as light, moisture, heat, oxygen, and pollutants (Evans et al., 1992; Hon, 1994). The weathering process of wood is primarily a surface phenomenon although the cracks and checks that develop during weathering can be sensitive to fungal attack and lead to more severe destruction of wood. Heat treatment is one of the processes used to modify the properties of wood. Heat-treated wood is considered an eco-friendly alternative to chemically impregnated wood materials. The chemical modifications that occur in wood during treatment at high temperatures are accompanied by several favourable changes in its physical properties, including reduced shrinkage and swelling, improved biological durability, low equilibrium moisture content, enhanced weather resistance, a decorative dark color, improved thermal insulation properties and better decay resistance (Shi et al.,2007; Kocaefe et al.2007; Shi et al.,2007; Alén et al. 2002; Sivonen et al. 2002).

Different methods for the thermal modification of wood have been developed in France, Finland, Netherlands and Germany since the middle of the last century. What all the heat processes have in common is the treatment of wood at elevated temperatures in the range of 160°C to 260°C. The differences between the processes are in the process conditions (steps, treatment atmosphere, steaming, wet or dry process, use of oils, steering schedules, etc.) (Rapp. A.O., 2001). The main targets for industrial heat-treatment are improved dimensional stability, increased biological durability, enhanced weather resistance, and decreased shrinking and swelling of wood. The industrial scale wood heat-treatment process, "ThermoWood", has been developed at the Finnish Research Center VTT in collaboration with the Finnish industry (ThermoWood Handbook, 2003). The Thermo-Wood process is based on heating the wood material to high temperatures (above 180°C) under normal pressure while protecting it with water vapor (ThermoWood Handbook, 2003). Water vapor protects the wood from burning and cracking, and it also affects the chemical changes taking place in wood. This is the method used for all the work done in this article.

From the mathematical point of view, the high temperature heat treatment of wood can be treated as a simultaneous heat and mass transfer through a porous medium (Kocaefe et al., 2006; Younsi et al., 2006; Majumdar and Deb, 2003; Kocaefe et al., 2007; Younsi et al., 2007; Younsi et al., 2008). Leading edge heats up faster compared to other surfaces. Therefore, this high temperature heat treatment has to be studied along with the flow field as a conjugate problem. Hence, it is necessary to solve the Navier-Stokes equations in the vicinity of the wood in order to determine the boundary conditions of the transport equations in the medium and consequently to resolve the complete thermal problem (Younsi et al., 2008). The suggested model, which uses a three-dimensional diffusion model, is an attempt to improve the description of the coupled heat and mass transfer process during heat treatment of wood, which is the originality of this study.

In the current work, the turbulent three-dimensional Navier-Stokes equations together with the energy and concentration equations for the flow domain coupled with the energy and mass conservation equations for wood are solved to study the high temperature wood heat treatment process based on the ThermoWood technology. The predictions of the model were compared with the experimental data under different conditions to validate the model.

NOMENCLATURE

C	$[kg.m^{-3}]$	Concentration
C_p	$[J.kg^{-1}.K^{-1}]$	Heat capacity
D	$[m^2.s^{-1}]$	Diffusion coefficient
P_k	$[m^2.s^{-3}]$	Shear production of turbulent kinetic energy
k_q	$[W.m^{-1}.K^{-1}]$	Thermal conductivity
M	kg H_2O.(kg solid)$^{-1}$]	Moisture content
P	[Pa]	Partial pressure of water vapor in wood
t	[s]	Time
T	[K]	Temperature
x,y,z	[m]	Spatial coordinates
u,v,w	$[m.s^{-1}]$	Velocity components

Special characters

ρ	$[kg.m^{-3}]$	Dry body density
μ	$[kg.m^{-1}.s^{-1}]$	Dynamic viscosity
μ_t	$[kg.m^{-1}.s^{-1}]$	Turbulent eddy viscosity
ε		Viscous dissipation in turbulent flow
$\sigma_{k,\varepsilon,T,C}$		Turbulent Prandtl numbers of k, ε, T,C
ΔH_{lv}	$[J.kg^{-1}]$	Latent heat of vaporization

Subscripts

0	Initial
f	Fluid
final	Final
g	Gas
l	Liquid
v	Vapor

MATHEMATICAL FORMULATION

The problem can be viewed as a batch of wood boards exposed to high convective heating in an inert atmosphere (see Figure 1). The approach adopted in this study involves the solution of the hydrodynamics problem simultaneously with the heat and mass transfer in wood. It is assumed that the flow field is turbulent, the porous system is three-dimensional, the shrinkage and gravity effects are negligible, no degradation of the solid occurs, and there is no heat generation inside the wood. Figure 1 shows the geometry of the physical model.

Governing Equations for the Flow Field

Based on the average velocities measured in the furnace, the flow regime is expected to be turbulent. The three-dimensional Navier-Stokes, energy, and concentration equations considered are as follows (Younsi et al., 2008):

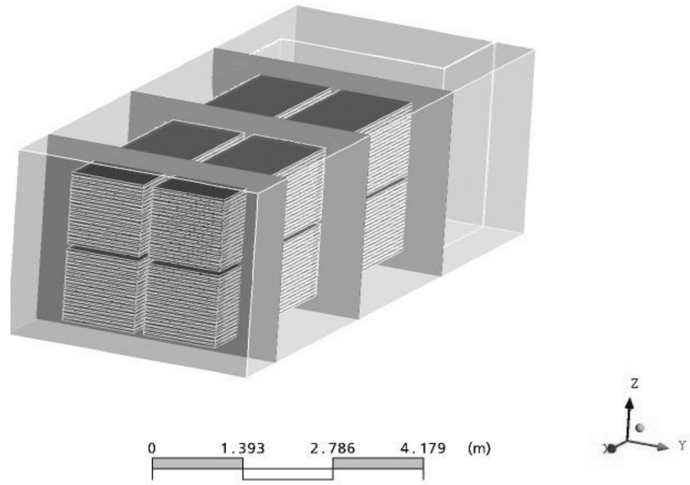


Figure 1 Global View of the Physical Model

<u>Continuity</u>

$$\frac{\partial(\rho_f u)}{\partial x}+\frac{\partial(\rho_f v)}{\partial y}+\frac{\partial(\rho_f w)}{\partial z}=0 \quad (1)$$

<u>Momentum</u>

X-momentum

$$\frac{\partial}{\partial t}(\rho_f u)+\frac{\partial}{\partial x}(\rho_f uu)+\frac{\partial}{\partial y}(\rho_f uv)+\frac{\partial}{\partial z}(\rho_f uw)=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left[(\mu_{eff})\frac{\partial u}{\partial x}\right]+\frac{\partial}{\partial y}\left[(\mu_{eff})\frac{\partial u}{\partial y}\right]+\frac{\partial}{\partial z}\left[(\mu_{eff})\frac{\partial u}{\partial z}\right] \quad (2)$$

Y-momentum

$$\frac{\partial}{\partial t}(\rho_f v)+\frac{\partial}{\partial x}(\rho_f uv)+\frac{\partial}{\partial y}(\rho_f vv)+\frac{\partial}{\partial z}(\rho_f vw)=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left[(\mu_{eff})\frac{\partial v}{\partial x}\right]+\frac{\partial}{\partial y}\left[(\mu_{eff})\frac{\partial v}{\partial y}\right]+\frac{\partial}{\partial z}\left[(\mu_{eff})\frac{\partial v}{\partial z}\right] \quad (3)$$

Z-momentum

$$\frac{\partial}{\partial t}(\rho_f w)+\frac{\partial}{\partial x}(\rho_f uw)+\frac{\partial}{\partial y}(\rho_f vw)+\frac{\partial}{\partial z}(\rho_f ww)=-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left[(\mu_{eff})\frac{\partial w}{\partial x}\right]+\frac{\partial}{\partial y}\left[(\mu_{eff})\frac{\partial w}{\partial y}\right]+\frac{\partial}{\partial z}\left[(\mu_{eff})\frac{\partial w}{\partial z}\right] \quad (4)$$

<u>Energy equation</u>

$$\frac{\partial}{\partial t}(\rho_f c_{pf}T)+\frac{\partial}{\partial x}(\rho_f uc_{pf}T)+\frac{\partial}{\partial y}(\rho_f vc_{pf}T)+\frac{\partial}{\partial z}(\rho_f wc_{pf}T)=\frac{\partial}{\partial x}\left[k_{eff}\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_{eff}\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[k_{eff}\frac{\partial T}{\partial z}\right] \quad (5)$$

<u>Concentration equation</u>

$$\frac{\partial}{\partial t}(\rho_f C)+\frac{\partial}{\partial x}(\rho_f uC)+\frac{\partial}{\partial y}(\rho_f vC)+\frac{\partial}{\partial z}(\rho_f wC)=\frac{\partial}{\partial x}\left[D_{eff}\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_{eff}\frac{\partial C}{\partial y}\right]+\frac{\partial}{\partial z}\left[D_{eff}\frac{\partial C}{\partial z}\right] \quad (6)$$

<u>The Standard k–ε Model:</u>

k-Eddy kinetic energy

$$\frac{\partial}{\partial t}(\rho_f k)+\frac{\partial}{\partial x}(\rho_f uk)+\frac{\partial}{\partial y}(\rho_f vk)+\frac{\partial}{\partial z}(\rho_f wk)=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right]+P_k-\rho_f\varepsilon \quad (7)$$

ε-Rate of dissipation of turbulence energy

$$\frac{\partial}{\partial t}(\rho_f \varepsilon)+\frac{\partial}{\partial x}(\rho_f u\varepsilon)+\frac{\partial}{\partial y}(\rho_f v\varepsilon)+\frac{\partial}{\partial z}(\rho_f w\varepsilon)=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right]+\frac{\varepsilon}{k}(C_1P_k-C_2\rho_f\varepsilon) \quad (8)$$

$$\mu_{eff}=\mu+\mu_t\,,\ \ k_{eff}=k_q+\mu_t c_{pf}/\sigma_T\,,\ \ D_{eff}=D+\mu_t/\sigma_C\,,\ \ \mu_t=C_\mu\rho_f k^2/\varepsilon$$

In the above equations μ_t is turbulent dynamic viscosity, P_k is the production of turbulent kinetic energy due to shearing, σ_k, σ_ε, σ_T and σ_C are turbulent Prandtl numbers defined for the relevant variable. The values of the model constants for all models considered are σ_k=1.0, σ_ε=1.4, σ_T=1.0, σ_C=1.0, C_1=1.44, C_2=1.92, C_μ=0.09

Governing Equations for Wood

Considering the system described above, the coupled heat and mass transfer equations based on energy conservation for a porous wood material can be written as (Younsi et al., 2006):

Heat transfer

$$\rho_m \frac{\partial h_m}{\partial t} = \frac{\partial}{\partial x}\left(k_{qx}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(k_{qy}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{qz}\frac{\partial T}{\partial z}\right) \tag{9}$$

Moisture transfer

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D_x\frac{\partial M}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_y\frac{\partial M}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial M}{\partial z}\right) \tag{10}$$

Initial and Boundary Conditions

The initial conditions can be expressed as:

$$T(x,y,z,0) = T_0 \;,\; M(x,y,z,0) = M_0 \tag{11}$$

The equations based on the continuity of the state variables and their respective fluxes at the interface were used as boundary conditions for both problems and are given by (Younsi et al., 2008):

Temperature continuity: $T_f = T_s$ (12)

Concentration continuity: $C_f = C(T,M)_s$ (13)

$$\textit{Heat balance:}\left[k_M\frac{\partial M}{\partial n} + k_{eff}\frac{\partial T}{\partial n}\right] = \Delta H_{lv} D\frac{\partial C_f}{\partial n} + k_f\frac{\partial T}{\partial n} \tag{14}$$

$$\textit{Species flux balance:}\left[D_M\frac{\partial M}{\partial n} + D_T\frac{\partial T}{\partial n}\right] = D\frac{\partial C_f}{\partial n} \tag{15}$$

The inflow and outflow conditions for the flow field are given as follows:

$$\begin{aligned} &\textit{Inflow} \Rightarrow \{u = U_g,\ v = 0,\ w = 0, T = T_g, C = C_g, k = k_{in}, \varepsilon = \varepsilon_{in} \\ &\textit{Outflow} \Rightarrow \{P = 0, \partial T/\partial x = 0, \partial C/\partial x = 0, \partial k/\partial x = 0, \partial\varepsilon/\partial x = 0 \end{aligned} \tag{16}$$

The thermo-physical properties of jack pine and diffusion coefficients are given elsewhere (Younsi et al., 2008).The hydrodynamic flow in the fluid domain is obtained by using a commercial software (ANSYS-CFX10, 2005). A finite-difference computer subprogram was developed to solve the set of equations for the heat and mass transfer in wood and incorporated into the ANSYS-CFX10 code. The solution of the matrix at each step is obtained using the Gauss-Seidel iterative method. The CPU time taken for simulating 48h of heat treatment process is 2h on a Dell-Pentium4 2.5GHz machine.

EXPERIMENTAL APPARATUS

In this work, the wood is treated with the Finnish ThermoWood technology which uses superheated steam at 130°C and air at atmospheric pressure as a shielding gas. An industrial furnace under relatively mild conditions (<220°C) was used to treat the wood boards. The process used consists of five regimes as shown in Figure 2: **I** Heating, **II** 1st drying, **III** 2nd drying, **IV** Treatment, **V** Cooling. All boards used in this experiment originated from the same batch of 0.025m×0.15m×3m pre-dried jack pine boards with an initial moisture content of MC ≈ 17%. The initial moisture content of the wood boards was measured before each experiment using a wood moisture meter (Delmhorst RDM-2S) with an accuracy of 0.1%. The range of this hygrometer is between 4.5%-60%. The temperatures at predetermined positions within the boards were measured every 60s by means of T-type thermocouples (Copper-Constantan) which were connected to the data acquisition system (Keithley 2700). The accuracy of the thermocouples is 3.8%.

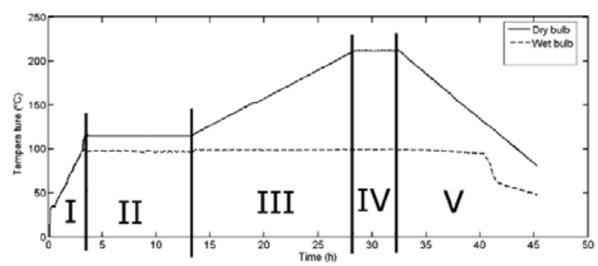


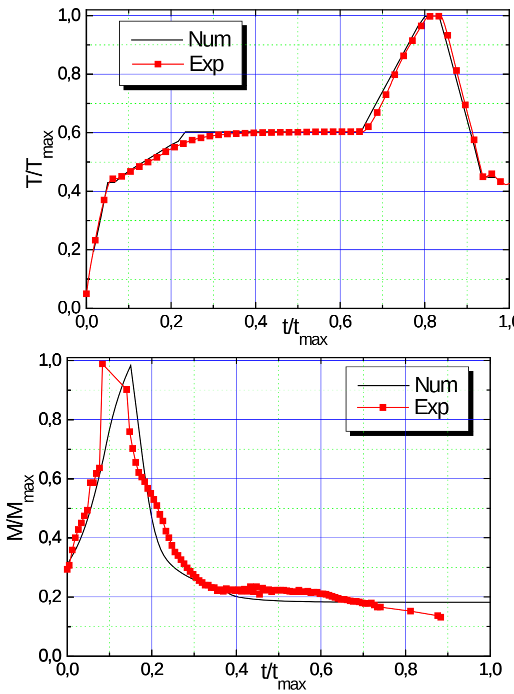
Figure 2 Typical ThermoWood Heat Treatment Schedule (ThermoWood Handbook, 2003)

RESULTS AND DISCUSSION

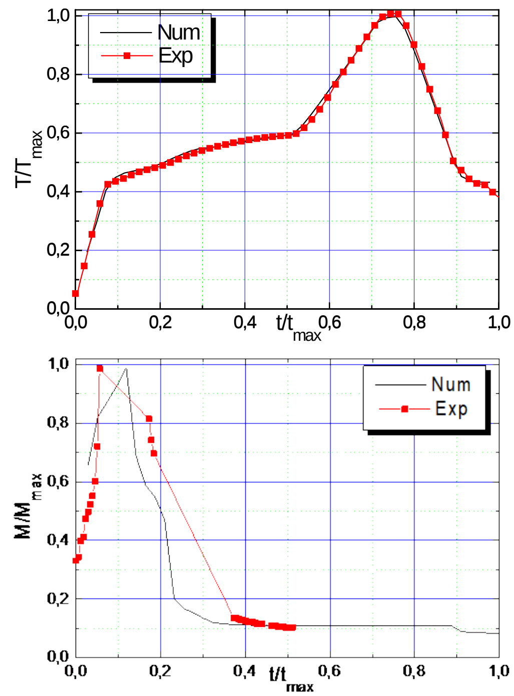
During the high temperature heat treatment of wood, it is important to know how the temperature and moisture distributions change with time. This information can be used to adjust the treatment parameters and, consequently, to control the quality of final product more effectively. The present mathematical model successfully predicts these profiles.

The validation of the mathematical model was carried out by comparing the predictions of the model with the experimental data obtained during the high temperature treatment of jack pine in an industrial furnace which uses ThremoWood technology.

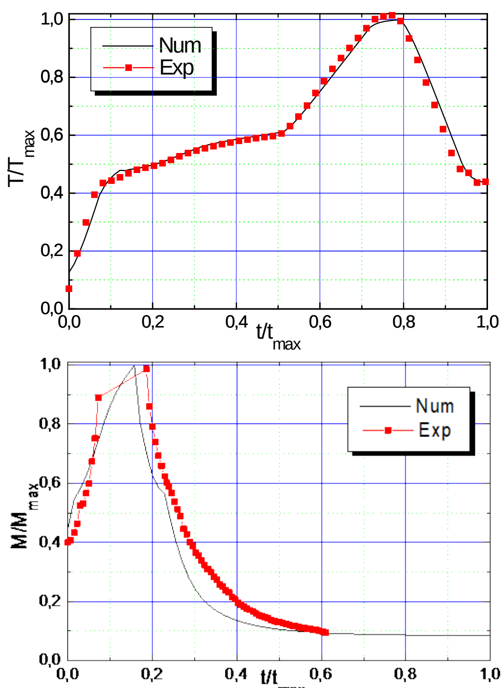
The normalized temperature and moisture content vs. time data are compared with the model predictions in Figure 3 for three different schedules. The main difference between the schedules is the amount of vapor and the duration of the test. In general, the model predictions are in good agreement with the experimental data. The slight difference between the shapes of the experimental curves giving the evolution of the normalized moisture content and the predicted ones might be due to the possible vaporisation of moisture in wood and lack of data on the wood thermophysical properties. During the heat treatment, the temperature increases and the average moisture content decreases almost linearly with time except at the beginning of the process due to the amount of steam and condensation during this period. This linearity is due to the influence of gas temperature which is also increased linearly with time.



Schedule 1



Schedule 3



Schedule 2

Figure 3. Comparison of Predicted and Experimental Normalized Temperature Evolution (left) and Normalized Moisture Content Evolution (right) During Heat Treatment for Different Schedules (Final Temperature $T_{g,final}$=210°C)

CONCLUSION

A study which involves the numerical prediction and experimental investigation of the high temperature heat treatment of wood based on ThermoWood technology has been carried out by solving turbulent three-dimensional Navier-Stokes equations for the flow field together with the conjugate heat and mass transfer in wood. The computational fluid dynamics software, ANSYS CFX10 was used to solve the coupled system of partial differential equations. The numerical code takes into account the moisture and/or temperature dependency of the thermodynamic, physical, and transport properties. Comparison of the temperature and moisture content profiles calculated by the model with those obtained from the experimental investigation are in reasonably good agreement.

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